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Neutronrefleksioner

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Published in:
Kvant - Tidskrift for fysik of Astronomi

Publication date:
2007

Document Version
Også kaldet Forlagets PDF

Link to publication

Citation for pulished version (APA):
Klösgen, B., & Hewitt Klenø, K. (2007). Neutronrefleksioner. Kvant - Tidskrift for fysik of Astronomi, 18(2), 32-33.

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Download date: 10. Jan. 2017

Neutron Reflections

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”Oil avoids water”: the colourful reflection patches on water surfaces give optical evidence of this everyday statement. Beams of neutrons instead of optical light are a new tool to investigate the properties of very thin layers. Here we tell about the principle, and give examples about neutron reflections.

Reflection from transparent surfaces!

Everybody has experienced the annoying presence of reflections when gazing across a showcase: even when looking perpendicularly through a glass window some 8% of the light is lost from transmission and found as undesired reflection!

Figure 1 exhibits a photo taken by myself when I was gazing into a museum from the outside: the reflections on the glass window overlapped with the impressions I got from the inside to an extent that the objects in the museum were almost indistinguishable. The French physicist Fresnel (1788-1828) did a thorough study of light refraction versus reflection. He condensed his findings into a still actual set of equations that describe the degree of reflection and transmission of an electromagnetic wave when it hits the interface between two media of different refractive index as depending on the incident angle.

Figure 1. Optical mix of transmitted light from inside a museum with reflections from street life.

A peculiar case is the one of total reflection that is found when light travels from the high density medium (n_{high}) into the low density (n_{low}) one (e.g. from water into air) - all light incident at an angle below the critical angle Θ_c (or bigger than a limiting incident angle) is reflected, and no light is transmitted.

Modern physics has extended the understanding of optics and integrated the interaction of particle waves.

Neutrons shining an interface

In 1924 de Broglie postulated that matter at high velocity can be envisaged as a wave where the wavelength $\lambda = \frac{h}{m \cdot v}$ is given by the particle mass m, its velocity v, and the Planck constant h. Ever since then many experiments have proved evidence of this so-called particle-wave dualism. Also neutron beams as generated in a reactor or spallation sources may be envisaged as waves; they exhibit typical optical features as interference, reflection, or diffraction. An example about reflectivity is shown in figure 2a for a neutron wave with λ=4.6Å incident on an interface between silicon and water. The critical angle $\theta_c = \arcsin\left(\frac{n_{low}}{n_{high}}\right)$ is very low as compared to the angles found for “real light”.

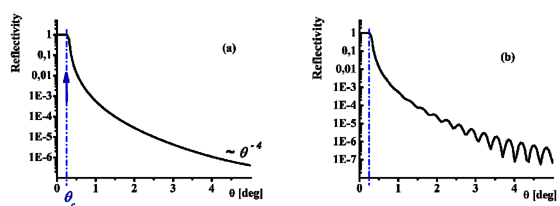

Figure 2. a, left: total internal reflection takes place at angles below a critical value Θ_c ; the intensity of the reflected beam decays as Θ^{-4} above Θ_c. b, right: the presence of an interfacial layer results in the modulations superimposed to the decay of the beam intensity.

Neutrons report about thin layers at interfaces

The colourful appearance of oily slicks on water (see figure 3) is due to interference of light that is partially reflected from the outer oil surface but as well is partially transmitted into the slick to be then reflected from the inner interface of the oil as it floats on the water surface. There is a difference on path length between these two rays that is equivalent to a phase shift and causes, in white light, the appearance of coloured fringes. The details of the pattern can be analysed to reveal the thickness of the thin oily layer.

In monochromatic light the fringes are seen as a modulation of intensity. Still, the wavelength of normal light imposes a limitation to layer analysis: no films thinner than roughly the wavelength itself can be examined.

Figure 3. An oil slick floating on water represents a thin film situated at the interface between the two bulk volumes of water and air.

Here the low wavelength of "particle light" is the escape: e.g. a neutron beam with a typical wavelength of ~5-10Å allows layer studies down to a that extension.

In a straightforward approach a sample carrier supporting a thin layer is first adjusted such that a neutron beam is grazing the surface as a parallel beam. Then the carrier is continuously turned such that the beam is incident from the denser medium at a very shallow angle to the surface: optically, this fulfils the conditions of total reflection and the neutron beam is totally reflected. Only after the incident angle gets beyond the critical angle limit, the intensity of the reflected beam decays. Due to the presence of the film, the situation is different from as figure 2a because a portion of the transmitted light is reflected as well from the inner surface of the thin layer. All reflected beams recombine by interference and yield, as a function of the incident angle, a so-called Kiessig-pattern as it is shown in figure 2b. In essence, the pattern is a fringe structure superimposed to the normal intensity decay of reflection. Details about the layer structure, as layer thickness and homogeneity, may be drawn from the analysis of the pattern. The method can be extended to the case of multilayers but then requires more complicated experiments as a series of sequential exposures, and the application of more sophisticated models to analyse the data.

What, for example, would we like to measure?

Functional sheets are abundant in living organisms. Future technology might aim at biomimetic systems that implement selected tasks, e.g. for use in a biosensor. An artificial film shall imitate a chosen biological process, like filtering waste components. Nature solves that kind of problem by functional proteins embedded into lipid bilayer membranes. In a device, one would immobilize the biomimetic layer on a carrier as a silicon wafer, and put a soft cushion of polymer below in order to comfort the protein (see figure 4a). The presence of the garbage is then detected spectroscopically.

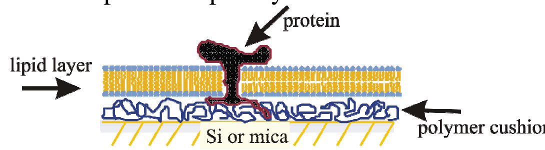

Figure 4a. Schematics of a supported biomimetic layer.

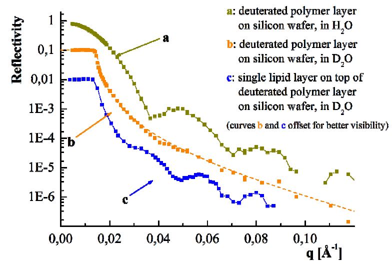

Figure 4b. Neutron reflectograms showing Kiessig fringes from a sandwiched film of polymer (~400Å) and a single lipid layer deposited thereupon (1.6Å), all assembled on a silicon wafer and measured in normal and in heavy water.

The path is suggestive but evolutionary results are not easy to copy, in part due to insufficient insight into basic properties of these composite systems. Protocols must be developed to build up the layer sandwich, and the results must be controlled. Neutron reflectivity experiments as shown in figure 4b report on the sequential build-up of the layers, and yield their structural details.

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Figure 5. Collaborators in control cabin of neutron reflectomer V6 at Hahn-Meitner-Institut, Berlin. Left: beamline responsible Roland Steitz introducing students (Sara Bruun and Søren B. Hansen from SDU, Odense) to remote control procedures while Tommy Nylander (from Lund University, Sweden) sets a meter. Right: Late night snapshot: tired but happy – students Kasia Wodzinska and Monika Stachura (from KU, Copenhagen).